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Parameter extrapolation to ungauged basins with a hydrological distributed model in a regional framework

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Abstract

A Regional Water Resources study was performed at basins within and draining to the Basque Country Region (N of Spain), with a total area of approximately 8500 km². The objective was to obtain daily and monthly long-term discharges in 567 points, most of them ungauged, with basin areas ranging from 0.25 to 1850 km². In order to extrapolate the calibrations at gauged points to the ungauged ones, a distributed and conceptually based model called TETIS was used. In TETIS the runoff production is modelled using five linked tanks at each cell with different outflow relationships at each tank, which represents the main hydrological processes as snowmelt, evapotranspiration, surface runoff, interflow and base flow. The routing along the channels' network couples its geomorphologic characteristics with the kinematic wave approach. The parameter estimation methodology tries to distinguish between the effective parameter used in the model at cell scale, and the watershed characteristic estimated from the available information, being the best estimation without losing its physical meaning. The relationship between them can be considered as a correction function or, in its simple form, a correction factor. The correction factor can take into account the model input errors, the temporal and spatial scale effects and the watershed characteristics. Therefore, it is reasonable to assume the correction factor is the same for each parameter to all cells within the watershed. This approach reduces dramatically the number of parameter to be calibrated, because only the common correction factors are calibrated instead of parameter maps (number of parameters times the number of cells). In this way, the calibration can be performed using automatic methodologies. In this work, the Shuffled Complex Evolution – University of Arizona, SCE-UA algorithm was used. The available recent year's data was used to calibrate the model in 20 of the most representative flow gauge stations in 18 basins with a Nash-Sutcliffe index higher than 0.6 (10 higher than 0.8). The calibrated correction factors at each basin were similar but not equal. The validation process (in time and space) was performed using the remaining data in all flow gauge stations (62), with 42 basins with a Nash-Sutcliffe index higher

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than 0.5 (25 higher than 0.7). Deficient calibration and validations were always related with flow gauge stations very close to the karstic springs. These results confirmed that it was feasible and efficient to use the SCE-UA algorithm for the automatic calibration of distributed conceptual models and the calibrated model could be used at ungauged basins. Finally, meteorological information from the past 50 years at a daily scale was used to generate a daily discharges series at 567 selected points.

1 Introduction: problem framework

Knowing water budgets for the basin and its subbasins allows water-resource managers to identify areas of greatest concern in the basin and make more informed decisions about conservation and remediation. A Regional Water Resources study was performed at basins within and draining to the Basque Country Region (N of Spain), with a total area of approximately 8500 km². The objective was to obtain daily and monthly long-term discharges in 567 points (initially 123 points, but at the end of the project more simulation points were demanded), obviously most of them ungauged, with basin areas ranging from 0.25 to 1850 km². The study area is officially divided into 21 hydrological systems with a total of 41 basins (Fig. 1), only 17 of them with at least one flow gauge station. Northern basins drain to the Bay of Biscay in the Atlantic Ocean with a humid climate, and southern basins drain to the Ebro River (which flows to the Mediterranean Sea) with a dry continental climate.

In this study, distributed modelling was proposed mainly:

- Due to the high number of simulation points and its vague definition at the beginning of the project.
- In order to extrapolate the calibrations at gauged points to the ungauged ones, without parameters regionalization but reproducing the natural spatial variability of the Hydrological Cycle.
- Because spatial information is available to be used in these type of models.

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Distributed models divide the catchment into a number of smaller areas (grid elements or subcatchments), which are assumed to be uniform with respect to their hydrologic parameters. There has been an “exponentially growing” recent interest in distributed hydrologic modelling that has been fuelled by the growing availability of GIS-related information (Schaake, 2003).

Temporal and spatial heterogeneity can be important in many hydrologic applications. The main processes of the hydrological cycle are variable in time and space. The temporal variation is observed in input temporal data as precipitation, potential evapotranspiration, temperature, etc. The spatial variation is mainly detected in soil properties, soil moisture, land use, etc., which are represented as maps. In some cases, simple aggregation of temporal fluctuations can misrepresent important physical processes. Different hydrological processes as runoff production and channel network routing are affected by this temporal and spatial variability which must be considered in the selected model (Wood et al., 1988 and Gan and Biftu, 1996).

Heuvelmans et al. (2004) studied the spatial variability of soil parameters using regionalisation schemes and concluded that clustering of parameter sets gives a more accurate result than the single parameter approach and is, therefore, the preferred technique for use in the parameterisation of ungauged sub-catchments as part of the simulation of a large river basin.

The scale effect by spatial and temporal aggregation of nonlinear processes is complex because the mean process response is not the result of the true mean parameter. The effective parameters usually are: physically senseless, non-stationary (they are not valid if used at different ranges obtained during calibration), and highly uncertain. The proposed solution is to use distributed modelling with a small temporal discretization.

The TETIS model has been developed at DIHMA-UPV and corresponds to a distributed hydrological conceptual model, which has been chosen because of their very good performance in different basins and climates; Vélez (2001), Vélez et al. (2002a, 2002b) and Francés et al. (2007). The TETIS model uses the kinematic wave methodology coupled to the basin geomorphologic characteristics in order to route the flow

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along the channel network. This procedure is known, according to Vélez (2001), as the “Geomorphologic Kinematic Wave” or GKW.

It is well known in hydrology that the quality in the output data of conceptual rainfall-runoff models depends on: the quality of input data, the model structure and the calibration process (Sorooshian et al., 1993; Lidén and Harlin, 2000 and Madsen, 2000). According to Grayson et al. (1992), conceptual models are better than physically based models since they are faster computationally and have less number of parameters when the suitable scale is adopted. Likewise, the conceptual models have a great capacity to compensate for errors and they are difficult to calibrate because they have been created for specific conditions. Sorooshian et al. (1993) indicate that conceptual rainfall-runoff models are difficult to calibrate using automatic methodologies. The successful application of a conceptual rainfall runoff model depends on how well the model is calibrated.

Beven (1989) has presented the limitations of current rainfall-runoff models and argued that the possible way forward must be based on a realistic assessment of predictive uncertainty. For this reason, Beven (1989) has pointed out that many distributed models are just lumped parameter models with a finer mesh, and a closer correspondence between model equations and field processes. This author also indicates that long-term records are required, which not always are available. In addition, the calibration must be performed under a physical point of view in order to interpret properly the parameters and to give them a correct interpretation to the spatial variability.

According to Beven (2000), the calibration of a model takes the same characteristics of an adjustment as a multiple regression, where the ideal parameters will be such that minimize the residual errors, but if there are residual errors it implies that uncertainty exists in the calibrated model. An important limitation of conceptual models, according to Gan and Burges (1990), is that they are not interpolative and there is no guarantee that the model predicts exactly a value during validation when it is used beyond the range of calibration. Likewise, it is recommended that a model should be tried in a range dramatically different from that they used during the calibration.

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The challenge is to estimate the best parameters set of distributed conceptual models. Due to the inability to accurately measure distributed physical properties of environmental systems, calibration against observed data is typically performed, which is most often achieved with limited rainfall-runoff data. The equifinality noted by Beven (1989) indicates that given the complexity of such models, many different combinations of parameter values may simulate the discharge equally well. These parameter sets may be located throughout many areas of the parameter space (Duan et al., 1992; Beven, 1989). This uncertainty of the appropriate parameter values yields predictive uncertainty, as has been demonstrated through applications of the Generalized Likelihood Uncertainty Estimation methodology (Beven and Binley, 1992; Freer et al., 1996; Beven, 2000).

Lidén and Harlin (2000) mentioned that the risk of obtaining a bad model performance, in a conceptual rainfall-runoff model, increases as the initial state moisture condition diminishes.

According to Refsgaars and Knudsen (1996), the main criteria for the evaluation of the performance of hydrological models include the joint visualization of the observed and simulated hydrographs, the general water balance, the efficiency coefficients and the dispersion graphs.

Efficiency indexes must be treated with care in the models, since reliability and validity are not equivalent and the first one does not imply the second one, increasing the size of a sample does not make the estimation more precise with regard to the simulation, it only diminishes the standard deviation. It is also true that a model cannot be estimated reliably based on a small sample, and even if a longer sample is obtained, it does not guarantee a more precise simulation (Duckstein et al., 1985).

The validation process is in charge of demonstrating that physical dominant processes in the basin have been simulated appropriately in a specific site. After validation the model is capable of performing predictions that satisfy the precision criteria previously established (Klemeš, 1988; Refsgaars and Knudsen, 1996; Senarath et al., 2000; Andersen et al., 2001). A fundamental principle in the validation process is that

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the model must be validated for the same type of applications for which it was originally developed (Klemeš, 1986). In addition, the information used during validation must be different enough from that used during calibration.

The purpose of this paper is to show a Regional Water Resources application using distributed conceptual modelling. The initial parameter maps are estimated using available information and then these maps can be globally corrected without losing their internal variability. This split-parameter structure allows for an extrapolating parameter from gauged sites to ungauged points using advantages of distributed models.

In the next section a brief description of the TETIS model is performed. Then the split-parameter structure and automatic calibration methodology are presented where the initial estimation of spatial parameters is briefly described. The altitude effect on the rainfall is presented and calibration results are exposed jointly with validation and simulation. Finally, some discussion issues and main conclusions obtained during the Water Resources Regional study are exposed.

2 Model description

The TETIS model is a conceptual distributed model where each grid cell represents a tank model with six tanks connected among them. A conceptual scheme of the vertical movement of the water at each cell can be observed in Fig. 2. The relationships among different tanks are different for every case, but always simple relationships were used. A more detailed description of the model appears in Vélez (2001), Vélez et al. (2002a, b) and Francés et al. (2007).

The first tank corresponds to the snow package, which can either exist or not. The snow melting process used in the model is the classic degree-day method, which is widely used in the scientific literature (Singh, 1989). For the Basque Country Region case study this tank was not included. The second tank corresponds to the static storage, where the only flow exiting is the evapotranspiration. This tank also represents the initial abstractions and pond surfaces. The surface storage is the third tank, where

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the available water that is not infiltrated can be drained superficially as surface runoff. The soil infiltration capacity has been associated with the soil saturated hydraulic conductivity. The fourth tank represents the gravitational storage; the percolation process is modelled according to both soil saturation conditions and the transport capacity, in vertical sense; the remaining water is available to feed the interflow. The fifth tank corresponds to the aquifer, where the vertical flow represents the system underground losses and the horizontal flow is the base flow. The last tank represent the channel at the cell, where each cell is connected to the downstream cell according to the drainage network. Indeed, it is a three-dimensional model. In the Fig. 3 the behavior of the horizontal flow in TETIS model is observed. All cells drain towards the downstream cell until they reach the channel. Once the channel is reached the flow routing is performed according to the GKW methodology.

The time series required during the model execution are discharge, rainfall, evapotranspiration, snow water equivalent and temperature in case that the snow exists. Cartographic information uses raster format maps. Digital Terrain Model (DTM) and soil properties (available water and saturated hydraulic conductivities) are obtained based on soils studies, land use, geological maps, edaphologic information, hydrogeological data and other environmental topics that could be interesting and are available at the study area.

The infiltration model and the flow channel routing model proposed in TETIS include a few correction factors which correct globally for the different soil properties maps instead of each cell value of the calibration maps, thus reducing dramatically the number of factors to be calibrated. This strategy allows for a fast and agile modification in different hydrological processes. These correction factors can be found using an automatic calibration. In general, if the TETIS model has been calibrated adequately these values must not change along the basin, thereby allowing extrapolation to ungauged subbasins.

TETIS model incorporates a correction factor (rainfall interpolation factor) which includes the variation of precipitation with the altitude. The rainfall interpolation factor

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has been called β and is given in mm/m. In those cases where it is not possible to calibrate the model due to a lack of water in the balance, then the rainfall interpolation factor can be included as an additional variable to be calibrated.

The routing along the channel network was carried out using the GKW, where nine geomorphologic parameters are required, which can be obtained from potential laws. The coefficients and the exponents of these potential relationships can be obtained with a geomorphologic regional study for hydrological homogeneous zones. The Basque Country Region uses the geomorphologic parameters recommended in scientific literature (Leopold et al., 1964; Vélez, 2001), since a geomorphologic regional study for hydrological homogeneous zones was not carried out.

All storages have relevancy inside the initial soil moisture conditions (state variables): snow pack supplied as snow water equivalent in mm. The static storage is given as a percentage of the maximum capacity of the static storage. The initial soil moisture in the surface storage, the gravitational storage and the aquifer are given as a water column in mm. Finally, the initial condition in the channel is supplied to the model as a percentage of the bankfull section. These initial condition variables are global, e.g. they have the same value for all cells and must be adjusted or calibrated by means of automatic or trial and error procedures. In the case study if the temporal scale was a daily scale, then it is possible to use a previous period of time to calibrate in order to generate initial soil moisture conditions as real as possible. Normally, a range between one and two months has been used as a previous period of time to calibrate to obtain an initial soil moisture condition, also known as a “warm up” period.

The TETIS model uses the inverse distance method to interpolate spatially temporal series of rainfall, evapotranspiration, temperature and the snow water equivalent. Due to the existence of numerous stations, it is necessary to indicate in the model the number of nearest stations to each cell, to carry out the spatial interpolation.

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3 Split-parameter structure and automatic calibration

The split-parameter structure refers to the way the model estimates the parameter maps. The parameter estimation methodology tries to distinguish between the effective parameter used in the model at cell scale, and the watershed characteristic estimated from the available information, being the best estimation without losing its physical meaning. The relationship between them can be considered as a correction function or, in its simple form, a correction factor (Francés et al., 2007).

Initially, the maps are estimated a priori using environmental and available information (Puricelli, 2003). Then, correction factors are used to modify globally the previously estimated maps. In this way, the spatial variability captured in the initial estimated maps is kept and a global change in magnitude of parameter maps is performed with correction factors (Francés et al., 2007). This approach reduces dramatically the number of parameters to be calibrated, because only the common correction factors are calibrated instead of parameter maps (number of parameters times the number of cells). The correction factor can take into account the model input errors, the temporal and spatial scale effects and the watershed characteristics. Therefore, it is reasonable to assume that the correction factor is the same for each parameter to all cells within the watershed. Finally, the calibration of the correction factors is performed if there are available observed episodes.

According to the hydraulic behavior at cell scale, the required maps and correction factors are related as follows:

- Maximum static storage: $H_u^* = CF_1 \cdot H_u$
- Vegetation cover index during ET: $\lambda_v^*(i) = CF_2 \cdot \lambda_v(i)$, $i = 1, \dots, 12$
- Infiltration at constant rate: $k_s^* = CF_3 \cdot k_s$
- Surface runoff velocity (linear reservoir): $v_h^* = CF_4 \cdot v_h$
- Percolation at constant rate: $k_p^* = CF_5 \cdot k_p$

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- Interflow velocity (linear reservoir): $k_{ss}^* = CF_6 \cdot k_s$
- Underground losses at constant rate: $k_{pp}^* = CF_7 \cdot 0,1 \cdot k_p$
- Base flow velocity (linear reservoir): $k_b^* = CF_8 \cdot k_p$
- Flow velocity: $v_f^*(t) = CF_9 \cdot v(t)$

5 The required maps are the maximum static storage or available water H_u , the vegetation cover index map λ_v , the saturated hydraulic conductivity of soil k_s , the surface runoff velocity v_h , and the saturated hydraulic conductivity of subsoil k_p . The flow velocity $v(t)$ is calculated according to the GKW procedure and correction factors CF_1, CF_2, \dots, CF_9 must be calibrated.

10 The next sections are dedicated to outline briefly the initial estimation of parameter maps and the calibration strategy.

3.1 The initial estimation of spatial parameters

The initial estimation of spatial parameters deals with the prior estimation of three soil properties, according to Puricelli (2003): available water and saturated hydraulic conductivities of soil and subsoil, respectively. This prior estimation is made of edaphologic and not strictly edaphologic information, based on available data. This implies the interpretation (or inference) of the land properties (Abbaspour and Moon, 1992), extending the analysis to ground mean values. This work requires the knowledge of factors affecting the selected variables and their impact. The statistical technique used during the map estimation is the multivariate weighted least-squares method, in which the three hydrological parameters were related to environmental variables, deduced from available information.

25 The proposed procedure was carried out in four stages: 1) Describing land properties showing their spatial variations. 2) Establishing a sampling criterion to obtain a discrete set of representative values at the work area. 3) Defining the general tendency of expected values. 4) Finally, obtaining the thematic maps of physical soil properties.

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The cartographic representations of environmental variables, land characteristic and soil properties are related to elements of the landscape. Such elements are related to the spatial distribution of hydrological properties. Consequently, it is possible to define two types of variables:

- 5 a) Main variables: directly related to the hydrologic behavior as soil and subsoil hydraulic conductivity and available water.
- b) Environmental variables: those variables capable of explaining part of the spatial variability of main variables.

The objective of the initial estimation is to obtain as reliable as possible the estimation of three main variables. Consequently, a reasonable way to analyze its spatial variability is based on its relation with environmental variables. In real life, the available environmental variables are geology, land use and edaphology, which use categorical scales and are plotted on a map by means of cartographic units. Thus, for example, in the case of litology, the categories correspond to the different types of rocks described in the geologic map. Each category has associated a set of values corresponding to different physical properties, which are based on continuous scales of values. This association is actually stored into a database, where each cartographic unit is a record and properties are the different fields, including modal values. It is considered that the spatial variability of soil properties is significantly smaller within each cartographic unit than among adjacent units.

In Fig. 4 these concepts are exposed graphically. A small region can be observed in part (1), whose physical properties are expressed at two cartographic units. According to cross section A-A', the variability of a physical property (k_s) between the cartographic units can be observed in part (2). Thus, it can also be verified that it is possible to define a general tendency of the values throughout this profile according to the expected spatial variability. Finally, if a cartographic unit is isolated, as shown in part (3), then it can be verified that a variability among the unit exists, which oscillates around its modal value.

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The distributed hydrological models force one to use different physical properties extracted from the cartographic units. This implies an interpretation and process of the categorical information in order to incorporate its variation.

5 The most significant environmental variables able to explain the spatial distribution and the variability of the saturated hydraulic conductivity are: topographic index, slope, curvature, cumulative area and geology (McKenzie and Austin, 1993 and Boer et al., 1996).

10 The relationship between the vegetation and the landscape has been extracted from DTM (Bolstad et al., 1998). The vegetation is a variable influenced by different edaphic qualities including the land use and vegetation coverage.

Once we've obtained the thematic layers corresponding to the main and environmental variables, the sampling scheme was based on assigning the modal value of each main variable to a portion of land which was considered as a sampling site. This portion of land is obtained from the intersection between all the cartographic units.

15 The mean values of the main and environmental variables were assigned to the new cartographic units. In the case of the main variables, the assigned weight was the area at each soil cartographic unit, as shown in Fig. 5. In the case of continuous environmental variables, the weight was the average value of all pixels affected by the intersection. The result was a finite number of distributed values on the study area, which represent the values of the main variables based on the spatial distribution of the environmental variables.

20 The method to estimate the parameter maps was based on the statistical adjustment among the environmental variables and the main variables. A classical statistical methodology as multivariate weighted least-squares was carried out because it is simple and can be easily adapted at cell scale. Different methodologies such as kriging, incorporating external information, could be applied to obtain the spatial distribution of the modal values among cartographic units, but those methods were not adopted because they are time-consuming.

25 The scheme of multivariate weighted least-squares proposed by Montgomery and

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Runger (1996) allows one to combine quantitative variables with categorical data and their interactions. The objective function to minimize is:

$$\sum_{i=1}^n \omega_i \left(y_i - \beta_0 - \sum_{j=1}^k \beta_j x_{ij} \right), \quad (1)$$

where y_i is the main variable, x_{ij} is the environmental variable j , corresponding to the main variable, ω_i is main variable weight, β_0 is the estimation value when all the environmental variables are null and β_j are the environmental factors.

The dummy variables (also known as indicator variables), are used to incorporate qualitative information in least-squares procedures (Montgomery and Runger, 1996). Thus, a new dummy variable can be defined as the product of the other two dummy variables.

Using this procedure the quantitative information is maximized, categorical or continuous, being able to incorporate qualitative information and maintaining the coherence with the previous physical knowledge of the main variable.

Finally, the results at each cell are processed using GIS in order to obtain the final thematic layers, adding a spatial term to the original cartographic units according to:

$$y_i^* = y_i + [E(y_i) - y_i^c]. \quad (2)$$

Since y_i^* is the estimated main variable value at cell i , y_i is the main variable value after the multivariate weighted least-squares at each cell in the cartographic unit. $E(y_i)$ is the expected value of the main variable for each cartographic unit, and y_i^c is the modal value of the main variable, assigned to each cartographic unit.

Finally, three maps of soil parameters are obtained and requested by model TETIS. Is shown in Fig. 6 the parameter map (H_u), obtained with the proposed initial estimation process, where the spatial variability among the Basque Country Region can be observed.

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3.2 Calibration procedure

The calibration of most complex hydrological conceptual models has been performed using traditional manual calibration, using the trial and error as suitable methodology. In this type of calibration it is necessary to be an expert user in order to obtain results in a fast and reliable form. The automatic calibration procedures need an initial region of the parameters (physical and feasible values), which can be similar to neighbour basins or hydrological and climatologically similar basins; Boyle et al. (2000).

The estimation of conceptual model parameters has proven to be a difficult task for several reasons, which include the existence of regions of attraction and multiple local optima. In the last few years numerous technologies have been developed for the automatic calibration. The methods of global search are the most popular, among them the genetic algorithms and the SCE-UA; Madsen (2000). Different authors have performed comparisons among different methods, among them the Simulated Annealing, Genetic Algorithm, MultiStart Simplex, MSX and the SCE-UA, emphasizing that the latter behaves better because the obtained parameters are more grouped and the number of evaluations of the objective function are lower (Duan et al., 1992; Sorooshian et al., 1993; Duan et al., 1994; Yapo et al., 1998 and Eckhardt and Arnold, 2001). Gan and Biftu (1996) mention that the SCE-UA is ideal to be operated by users who do not know the model and MSX needs an expert user and a process for stages, being more inefficient computationally whereas the SCE-UA obtains results in one execution.

And most recently, the Multiobjective Shuffled Complex Evolution Metropolis algorithm, proposed at the University of Arizona, is best suited for hydrologic model calibration applications that have small parameter sets and small model evaluation times (Tang et al., 2006 and Vrugt et al., 2006).

The model performance criteria in different optimization methods take different execution times, which influences the measurement of their behavior (Thyer et al., 1999). Gan and Burges (1990) mention that the mass balance is the most efficient criterion; even though iterative processes are used. They suggest that there is not a universal

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and valid scheme to calibrate a conceptual model following manual or automatic procedures. They recommend as optimization algorithms those based on direct search, considering them to be more robust. Numerous criteria can be found in the literature.

TETIS model includes different objective function criteria, such as (1) the error in volume (%errVol), obtained according to the expression:

$$\%errVol = \frac{V_o - \hat{V}_p}{V_o} \times 100\%, \quad (3)$$

where \hat{V}_p is the total simulated volume and V_o is the total observed volume. A positive value indicates an underestimation and negative values an overestimation, where zero is the expected value.

(2) The Root Mean Square Error, RMSE. This efficiency criterion is widely used:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n ((Q_i - \hat{Q}_i)^2)}{n}}, \quad (4)$$

where Q_i is the observed discharge at time i , \hat{Q}_i is the simulated value at time i and n is the total number of observation. This criterion looks for the minimum value of RMSE.

(3) The efficiency coefficient, E . It is estimated according to the expression:

$$E = 1 - \frac{\sum_{i=1}^n (\hat{Q}_i - Q_i)^2}{\sum_{i=1}^n (Q_i - \bar{Q})^2}, \quad (5)$$

Where, the mean value of the observed discharges is \bar{Q} . This is also known as the efficiency index of Nash and Sutcliffe (1970). This criterion is commonly used because it involves standardization of the residual variance and its expected value does not change with the length of the record or the runoff magnitude (Kachroo and Natale, 1992 has been cited by Kothiyari and Singh, 1999). A perfect adjustment suggests a value equal to one; if the value is zero it indicates that the model is not better if it is

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compared by one variable model (for example, an average value) and negative values indicate that the model behaves worse (Beven, 2000).

Recently, Bárdossy (2007) show how parameter sets can be transferred from gauged basins to closed ungauged catchments, if performance indexes and annual statistics in donor basins are good. Therefore, after the calibrating process at each basin, the correction factor sets could be used in ungauged catchments, if parameter maps have been estimated previously.

4 Case study: Basque Country Region

The Regional Water Resources study carried out at the Basque Country Region required an intensive information analysis and data process because collected data have different resolution, origin, size, quality and quantity. Additionally, other related topics to the case study as rainfall increment with altitude, calibration process, validation strategy and simulation are included in this section.

4.1 Hydrologic information

The meteorological and hydrological information have been supplied by different entities, namely: the National Meteorological Institute, INM; the Basque Government, GV; the Navarra Government, GN; the Statutory Deputation of Guipuzcoa, DFG; the Statutory Deputation of Biscay, DFV and the Hydrographic Federation of the Ebro River, CHE.

In the Basque Country Region case study a daily series has been used. Analyzing data was not an easy task, mainly because they were supplied from different sources and some data had a different reference hour. This was the case for pluviographic data with a reference time at 12:00 a.m. and pluviometric data with a reference time at 09:00 a.m. For this reason it was necessary to process the information in order that the reference time was the same in all stations. Basically, the modifications consist of

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estimating the daily value as the sum of two thirds of the observed value in the day plus one third of the registered value the next day.

The discharge information was supplied by twelve different entities with 143 gauge stations data but just 113 gauge stations were selected, from which 71 stations were used during the calibration and validation process. It is important to mention some of those stations required to re-establish the natural regime and some flow gauges present a delay with regard to the rain, so it was necessary to realize the respective modification.

The rainfall information consists of a data set of 248 rain gauge stations with a total of 3767 years of daily data. Additionally, 88 climatological stations were used to estimate the PET. In each cell in the case study the information of the three nearest stations was used in order to estimate the spatial distribution of the input variables.

4.2 The cartographic information

The original spatial information must be digitized in vectorial format. The information analysis, estimation methods, spatial distribution of hydrological parameters and final results are processed using GIS tools and databases.

The DTM was supplied with a cell size of 25 m×25 m. A gross discretization may lead to poor simulation results whereas a very fine discretization would require more input data and significantly increased computation time and space during automatic calibration with little increase in accuracy. Therefore, the cell size selected was 500 m×500 m. This decision implies that the remaining information must be processed to the same resolution. The DTM was used to extract the basic information: flow direction map to establish connectivity among cells, the cumulative drainage area used to estimate flow velocity using GKW procedure, the slope map used to calculate the runoff velocity and flow velocity using GKW method.

In addition, based on available information as topology, land use, lithology and geology four parameter maps have been obtained, that maps are the parameter maps required by TETIS model: the three main soil characteristics (available water and saturated

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hydraulic conductivities) and the vegetation index cover map as mentioned in previous section.

4.3 Rainfall increment with altitude

In those situations in which the precipitation data network does not have rain gauge stations located at high elevations, the main risk is to underestimate the precipitation value at high points. This effect could be possibly the greater source of error in the water balance (Daly, 1994).

In the Basque Country Region case study it was initially supposed that the correlation between rainfall and elevation does not exist ($\beta=0.0$), which contradicts the observed data on some rain gauge stations. The valley direction can determine the precipitation evolution in some zones of the Basque Country Region. In order to consider the variation of the precipitation with the altitude, it was necessary to estimate this gradient. Part of the supplied data consists of annual rainfall change rates with the elevation above sea level. These rates can be used to estimate a rainfall interpolation factor using the number of rainy days throughout the year. The obtained results were satisfactory once we clarified all the different types of influences on the precipitation.

For example, in the Oria River basin the elevation and precipitation analysis were carried out. If all data are analyzed jointly, the influence between precipitation and elevation cannot be detected, as shown in the Fig. 7 (continuous line). Therefore, the basin has been differentiated in two zones according to the prevailing wind direction. The results of the lower basin zone are shown in Fig. 7 (circle points and dashed line), where the topographic influence is quantifiable around 90 mm, each 100 m. The constant of the equation indicates a coastal annual precipitation of approximately 1500 mm which is coherent with reality. In the upper basin sector (filled triangle and dashed dot line) a remarkable correlation is also made visible. It provides similar coefficients to the lower zone; 100 mm, each 100 meters.

In the case of the Oria River basin the analysis allowed one to conclude that the precipitation gradient is around 100 mm for each 100 m of elevation increment due mainly

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to the wind effects. This effect was considered in the model using the rainfall interpolation factor during calibration, which establishes the rate of change of the precipitation with altitude, since the underground losses are the only degree of freedom capable of adjusting the water balance, if we assumed no errors in the data. This is the reason that this study highlights the necessity to count on rain gauge networks sufficiently extensive to diminish the use of this global factor.

4.4 Automatic calibration

The process of automatic calibration was carried out using the SCE-UA methodology. This procedure was performed independently at every basin or hydrological system, considering that nearby basins must have a hydrological similar behavior. Additionally, during the calibration process as a priori division was proposed, basically because the northern basins must have different behavior than southern basins, but must be similar inside each region.

The TETIS model allows one to choose the objective function during the calibration process, in the case study the RMSE has been selected. In addition, automatic calibration procedures require a search range and the initial values which can be observed in Table 1. Nevertheless, in every particular case some of these values have been diminished or extended, as the hydrologist considers it suitable. This is quite important because the hydrologist experience and field knowledge are included the calibration process at this point.

The calibration process requires an iterative process, where correction factors are estimated automatically using SCE-UA, and then the analysis of the results is performed, checking the hydrological sense and the water balance in each hydrological system, in order to reduce the uncertainty associated with the parameter maps and model performance. The initial soil moisture conditions are not included during calibration because a warm-up period of one or two months was included.

In Table 2 one sees the correction factors and the rainfall interpolation factor (β) obtained after applying the automatic calibration method SCE-UA. The correction factor

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variability among basins is not too strong except for correction factors CF-3, CF-5 and β . However, important differences can be observed between north and south regions, especially for the mentioned variables. Only two basins were calibrated with underground losses; CF-7 is greater than zero and therefore β must be zero; both basins located in the South zone. Differences in magnitude among correction factors are explained due to correction factor globally modifies the parameter map and it is in charge of different hydrological process. For example, CF-3 and CF-6 globally correct the parameter map (k_s), but CF-3 is trying to modify the conductivities in order to improve the infiltration process and CF-6 is multiplying the conductivities in looking for a good representation of the horizontal flow movement along the cell represented as interflow. In this way the order of magnitude for each correction factor can be explained.

The results of the water balance using the calibrated correction factors are shown in Table 3. In the case of basins located in the north zone a high annual precipitation was observed, where IF is the most important component, and DR and BF show similar behavior. In southern basins the PPT and RET are lower and the relevant flow is BF, where DR and IF are not as important. These aspects can be confirmed with land use and cover maps, where forests are located in the north basins and vegetation changes when you move southward. The relief and geomorphologic configuration also contributes to this effect.

In Fig. 8 (part a) one sees that consecutively the monthly index improves with regard to the daily index, which is favourable when a water resource study is performed. In Fig. 8 (part b), for the studied zones, the relation was presented between the area and the monthly Nash and Sutcliffe efficiency index. In conclusion, excellent calibrations were obtained in 10 cases (with E daily over 0.8), acceptable results at 9 basins (E daily between 0.6 and 0.8) and the one case left was moderate (E daily equal to 0.5); the monthly efficiency indexes show excellent results in most cases.

In Fig. 9 the results are shown after the calibration process at “A3Z1 Altzola” gauge station located in Deba River basin, where the error in volume was -1.99% . The performance efficiency indexes were 0.90 and 0.95 for daily and monthly data, respectively.

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This calibration results can be considered as excellent.

4.5 Validation process

Distributed models must be validated temporally, spatially and spatial-temporally, according to the available data. The first case is the validation using the same gauge station used during the calibration but with a different period of time. Spatial validation is performed using the same period of time used during the calibration but in an other subbasin, usually located upstream. And the spatial-temporal validation is performed using a different period of time and a different gauge station. All these validation approaches were performed in the Basque Country Region; Table 4 contains the summary results, and the validation process was carried out using available data, therefore the validation period length varies from a few months until several years. Northern basins have shown a better performance than southern basins on a daily scale. But the southern basins showed a better efficiency index at the monthly scale. In general, the volume error was greater at the small basins. It was not possible to include all detailed validation results in this paper but they can be found at INTECSA-INARSA-UPV (2004).

The validation performed in other basins of the Basque Country Region, in general, were very good, with few exceptions, in which the wrong validation was explained due to bad quality information, a scale problem at small basins due to cell size, or strong karstic presence.

Figure 10 shows the behavior of the monthly efficiency index at the basins where the validation has been performed. Those negative indexes that indicate that validation was not satisfactory were not included in the graph. The results indicate that the monthly indexes improve with regard to the diaries; same behaviour was reported during calibration. According to the monthly efficiency indexes just 11 cases are not satisfactory (E monthly less than 0.5), 10 are acceptable (E monthly between 0.5 and 0.7) and rest of the 41 cases are excellent (E monthly over 0.7). On the daily scale 20 cases are not good, 17 can be considered as good and 25 are excellent.

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The northern basins show different characteristics among them, at in the case of the Ibaizabal River basin, where the Karrantza and Herradura Rivers show a very different behavior with regard to the nearest Nerbioi and Ibaizabal basins, although the Karrantza River presented poor quality data.

5 Once the tables were analyzed with the results of the temporal, spatial and spatial-temporal validation it is possible to conclude that the validation has been performed satisfactorily and it is feasible to proceed with a worthy simulation.

4.6 Simulation

10 The Basque Country Region includes a very extensive area, which has been divided into hydrographic basins. In this way, the number of points used during calibration was different to the number of points used in validation and different to the points used during the simulation. For example, the total area of the Deba River basin is 531.75 km² at the Bay of Biscay. The basin area at the most downstream flowgauge “A3Z1 Altzola” is 469 km², where TETIS model was calibrated using flow data at this site. The final

15 correction factors set was validated in the upstream subbasins “A2Z1Aixola”, “A1Z1 San Prudentzio”, “A1Z2 Zubillaga” and “A1Z3 Urkulu”, but the simulation process was also carried out in the total basin area at the Bay of Biscay. The same procedure was carried out at all the Country Basque basins and then simulations were performed at 123 points, including calibration and validation points.

20 The simulation process used the available information from 1951 or 1961 until 2000 and was calculated from all northern basins to the Bay of Biscay, and all southern basins to Ebro River. At each basin the water balance was performed. In the case of the Deba River basin (531.75 km²), the mean annual rainfall is 1614 mm, of which the evapotranspiration is approximately 761 mm, according to TETIS (with PET of

25 851 mm). The simulated flow value is 851 mm, without losses. The model distributed the flow in 29.1% as surface runoff, 46.8% as interflow and 24.6% as base flow. In Fig. 11 one sees the results of the simulation for the 50 studied years. These results indicate that the Deba River basin never exhausts the flow; the recessions are short in

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time, indicating that it is a basin with a permanent flow. A similar analysis was carried out to all basins in the Basque Country Region, according to the simulation results shown in Table 5. During the simulation process underground losses were considered only at some southern basins where water balance could not be adjusted properly and the northern basin shows more water resources than the southern, as was expected.

5 Discussion and conclusions

The main advantages in the use of distributed models are the capacity to represent the space variability of hydrological processes and the capacity to understand the main processes at the hillslope and river basin scale. The TETIS model estimates all hydrological flows that take place at hillslope and river basin scale. In this way, it is possible to explore the origin of the water resources and their implications in water management. The distributed models are spatially robust because they can give results at any point in the basin, most of them ungauged; they do not aggregate information and they can be useful at different time scales, from flash floods to water resources management. Another benefit of distributed modelling is the avoidance of the parameter regionalization (an implicit process in traditional models). This aspect does not result exclusively in an economic saving but avoids sources of additional errors and uncertainties.

The split-parameter structure proposed is fundamental in order to calibrate the distributed conceptual models, basically because the number of parameters needed calibrate is dramatically reduced from cell number times parameter maps to just nine correction factors. But previously it required an initial estimation of parameter maps and then the correction factor calibration could be carried out. Therefore, this parameter structure could be adapted to other distributed models.

Distributed models required a relatively expensive initial calibration and validation process. However, the simulation was processed at many points with a comparatively low differential cost. For this reason increasing the output points made an economically and competitive approach. In fact, later studies at the Basque Country Region involved

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567 points with a reduced cost allowing one to overcome different studies, such as: risk analysis on small hydraulic projects, environmental flows in regulated rivers, maps of specific environmental necessities, underground water resources and environmental necessities, etc.

5 The Basque Country Region River basins were a typical example where it was observed that water quantity estimation is feasible and reliable using the TETIS model. Also, it was possible to obtain different runoff components and to observe the water balance inside each basin and subbasins. This type of study served to establish the water conditions at natural basins and areas of great concern, where using the water
10 balance of the observed 40 or 50 years could be feasible to forecast the future behavior of the hydrological system, which serves to make better decisions about planning, management, conservation and remediation.

The selected model is not a groundwater model and it is not able to simulate karstic effects and explain the bad performance of the model in small areas. The information
15 quality was an important factor to be considered because the basin located in the north showed better and consistent records than the southern basins. The hydrologic behaviour of the north basins is similar among them and different compared to the southern basins, as initially assumed. All differences in flow components among the basins could be finally explained.

20 The uncertainty in the data makes necessary the use of underground losses because in some basins it was not possible to adjust the water balance, which could be due to short-time series, inconsistency and lack of data. The scale effect observed in the small basins during calibration and validation could be lower if the cell size is reduced, but more studies are required.

25 The rainfall interpolation factor was important in some Basque Country Region basins because this eliminated the underground losses and allowed for closure of the water balance in most basins. Therefore, it was necessary to include it during the simulation process.

In general, the calibration and validation process can be considered as successful

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because efficiency indexes and volume error were found to be in admissible ranges in most cases; in those cases where it was not satisfactory the reason was identified. The calibration and validation results indicated that the worst calibration set was obtained in small, karstic or poor data basins. The detailed results of this study can be observed in INTECSA-INARSA-UPV (2004).

In general, the use of distributed modeling for the estimation of the water resources in natural basins is feasible and efficient, as shown in the Basque Country Region application. These results suggest that the extrapolating parameter used during the split-parameter structure was successfully carried out and could be used in other basin projects in order to extend and generalize this methodology.

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Table 1. Range and initial value of the correction factors used by the SCE-UA calibration method at Basque Country Region.

Correction Factor	Min.	Max.	Initial value
CF-1 Static storage	0.50	3.00	1.00
CF-2 Evapotranspiration	0.70	1.50	1.00
CF-3 Infiltration	0.00	0.40	0.10
CF-4 Surface runoff	0.00	0.8	0.30
CF-5 Percolation	0.00	0.40	0.05
CF-6 Interflow	100.	2000.	300.
CF-7 Underground losses	0.00	0.20	0.00
CF-8 Base flow	20.0	200.0	50.0
CF-9 Flow velocity	0.60	1.50	1.00
β rainfall interpolation factor	0.0	0.05	0.001

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Table 2. Summary of calibration results at selected gauge stations at Basque Country Region (CF: correction factors, β is the rainfall interpolation factor).

Basin	Gauge station	CF-1	CF-2	CF-3	CF-4	CF-5	CF-6	CF-7	CF-8	CF-9	β
Oiartzun	E1Z1 Oiartzun	1.67	1.04	0.068	0.421	0.040	449	0.000	38.8	1.34	0.0000
Urumea	CHN105 Ereñozu	1.00	0.97	0.096	0.214	0.043	290	0.000	56.9	1.31	0.0025
Oria	C9Z1 Lasarte	1.25	1.00	0.037	0.135	0.026	399	0.000	30.1	1.22	0.0013
Oria	C3T1 Amundarain	0.81	0.81	0.045	0.325	0.005	688	0.000	252.8	1.22	0.0070
Urola	CHN109 Etxabe	0.90	0.92	0.052	0.333	0.031	333	0.000	43.8	1.30	0.0025
Deba	A3Z1 Alitzola	1.08	0.97	0.053	0.397	0.021	355	0.000	36.1	1.30	0.0022
Artibai	AR01 Iruzubieta	1.00	0.92	0.029	0.256	0.030	373	0.000	87.4	1.30	0.0000
Lea	LE01 Aulestia	0.70	0.83	0.040	0.200	0.034	466	0.000	102.0	0.97	0.0000
Oka	OK01 Muxika	0.63	0.87	0.027	0.141	0.020	211	0.000	25.3	1.31	0.0015
Ibaizabal	NB05 Abusu	1.00	1.00	0.035	0.438	0.015	510	0.000	24.2	1.56	0.0031
Ibaizabal	KD01 Balmaseda	1.00	1.00	0.070	0.438	0.035	320	0.000	45.8	1.56	0.0031
Agüera	CHN186 Guriezo	0.70	1.00	0.029	0.455	0.020	747	0.000	162.1	1.39	0.0000
Karrantza	KR01 Karrantza	1.19	0.95	0.039	0.473	0.024	221	0.000	28.3	1.23	0.0000
Omecillo	CHE188 Berguenda	1.72	1.00	0.059	0.290	0.021	150	0.000	69.5	1.31	0.0000
Baia	CHE165 Miranda	0.90	0.90	0.031	0.263	0.016	138	0.000	117.9	1.28	0.0040
Zadorra	CHE074 Arce	0.80	1.05	0.150	0.400	0.030	500	0.000	95.0	1.40	0.0060
Inglares	OCIO Ocio	1.38	1.08	0.071	0.147	0.248	855	0.080	30.1	0.98	0.0000
Ega	G313 Ancin	1.20	0.71	0.288	0.196	0.029	905	0.006	33.6	1.14	0.0000
Ega	SA05 Zarpia	0.82	1.06	0.680	0.173	0.182	829	0.000	44.0	0.92	0.0140
Arakil	G433 Etxarren	1.00	0.99	0.096	0.236	0.020	622	0.000	126.8	1.33	0.0035

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Table 3. Summary of water balance after calibration process (PPT: Precipitation, PET: Potential evapotranspiration, RET: Real evapotranspiration, Q obs: Observed discharge, Q sim: Simulated discharge, UL: underground losses, DR: Surface runoff, IF: Interflow, BF: Base flow, %errVol: percentage of error in volume, E daily: daily efficiency index and E monthly: monthly efficiency index).

Basin	Gauge station	Area km ²	PPT mm/year	PET mm/year	RET mm/year	Q Obs mm/year	Q Sim mm/year	UL mm/year	DR %	IF %	BF %	%errVol	E daily	E monthly
Oiartzun	E1Z1 Oiartzun	57.25	1975	856	791	1281	1182	0	11	49	40	1.82	0.87	0.96
Urumea	CHN105 Ereñozu	213.00	2341	829	792	1598	1546	0	3.6	60	37	-5.97	0.82	0.93
Oria	C9Z1 Lasarte	805.50	1643	822	754	797	886	0	27	39	35	0.82	0.93	0.98
Oria	C3T1 Amundarain	16.25	2167	632	602	1674	1566	0	25	59	16	-13.14	0.68	0.77
Urola	CHN109 Etxabe	310.50	1589	794	720	934	867	0	24	41	35	-9.66	0.91	0.96
Deba	A3Z1 Altzola	469.00	1597	851	758	636	837	0	28	48	25	-1.99	0.90	0.95
Artibai	AR01 Iruzubietta	25.50	1594	800	753	571	838	0	31	41	28	-6.60	0.60	0.67
Lea	LE01 Aulestia	37.75	1519	726	664	692	857	0	30	35	35	-4.36	0.78	0.82
Oka	OK01 Muxika	28.75	1497	763	671	788	824	0	32	37	31	-3.14	0.81	0.90
Ibaizabal	NB05 Abusu	1021.00	1436	924	768	575	667	0	33	43	24	-2.31	0.79	0.90
Ibaizabal	KD01 Balmaseda	208.75	1321	897	526	736	793	0	20	43	37	-18.69	0.78	0.78
Agüera	CHN186 Guriezo	118.75	1273	799	629	1257	640	0	36	41	23	-36.57	0.73	0.80
Karrantza	KR01 Karrantza	114.75	1325	787	687	525	638	0	36	41	23	-6.71	0.86	0.89
Omecillo	CHE188 Berguenda	345.75	776	956	529	244	246	0	28	24	47	1.86	0.75	0.94
Baia	CHE165 Miranda	306.75	1066	741	547	595	517	0	28	36	36	-12.68	0.81	0.90
Zadorra	CHE074 Arce	1358.50	1012	934	518	441	491	0	12	39	49	21.16	0.67	0.90
Inglares	OCIO Ocio	86.00	754	1026	596	200	110	48	16	1.4	82	-6.43	0.79	0.77
Ega	G313 Ancin	472.50	871	655	487	270	369	14	2.4	28	70	2.59	0.82	0.91
Ega	SA05 Zarpia	11.00	1871	967	818	760	1049	0	0	1.5	99	34.07	0.50	0.48
Arakil	G433 Etxarren	401.50	1314	765	559	692	751	0	25	45	31	7.87	0.84	0.93

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Table 4. Spatial, temporal and spatial-temporal validation results at the Basque Country Region (N° years: validation period length, Obs Vol: observed volume, Sim Vol: Simulated volume, %errVol: Error in volume (%), E daily: daily efficiency index and E monthly: monthly efficiency index).

Basin	Gauge station	Area km ²	N° years	Obs Vol Hm ³	Sim Vol Hm ³	%errVol	E daily	E monthly
Bidasoa	F1Z1 Endara	5.75	3.0	33.9	27.7	-18.2	0.00	0.71
Oiartzun	CHN107 Oiartzun	35.50	30.3	1587.8	1333.6	-18.8	0.67	0.66
Urumea	CHN105 Ereñozu	213.00	31.3	10645.5	10150.5	-4.7	0.75	0.88
Urumea	D2Z1 Ereñozu	212.50	8.2	2509.8	2513.5	0.1	0.83	0.79
Urumea	D1W1 Añarbe	46.75	1.1	83.5	96.0	15.0	0.63	0.96
Oria	C2Z1 Agauntza	73.00	13.6	623.2	662.1	6.2	0.80	0.89
Oria	C7Z1 Belauntza	32.75	10.1	367.2	372.7	1.5	0.67	0.83
Oria	C8Z1 Andoain L	114.75	5.7	723.7	707.5	-2.2	0.78	0.95
Oria	CHN080 Andoain O	785.25	48.3	32903.2	31942.0	-2.9	0.68	0.71
Oria	C5Z1 Alegia	344.00	6.9	1356.7	1262.2	-7.0	0.87	0.95
Oria	C3T1 Amundarain	16.25	15.1	403.5	341.6	-15.3	0.64	0.75
Oria	C1Z2 Estanda	57.00	9.4	331.9	289.6	-12.7	0.82	0.90
Urola	CHN109 Etxabe	310.50	9.9	2868.0	2524.1	-12.0	0.88	0.91
Urola	B1Z2 Ibai Eder	64.50	9.9	513.3	542.4	5.7	0.85	0.94
Urola	B2S1 Granadaerre	2.25	9.0	48.8	17.0	-65.1	0.35	0.01
Urola	B1Z1 Aitzu	59.75	1.8	58.8	81.4	38.4	0.79	0.78
Urola	B2Z1 Aizarnazabal	277.50	4.7	1007.0	992.2	-1.5	0.92	0.95
Deba	A2Z1 Aixola	4.50	14.5	43.2	55.3	27.9	-0.09	0.43
Deba	A1Z3 Urkulu	8.00	13.0	78.8	81.8	3.7	0.69	0.86
Deba	A1Z2 Zubillaga	106.25	11.4	961.5	905.1	-5.9	0.80	0.93
Deba	A1Z1 San Prudentzio	127.25	5.5	375.4	320.7	-14.6	0.77	0.88
Artibai	AR01 Iruzubieta	25.50	13.9	193.0	223.0	15.6	0.42	0.14
Artibai	CHN141 Berriatua	94.00	30.3	2742.9	2117.3	-22.8	0.24	0.41
Lea	LE01 Aulestia	37.75	13.9	338.7	347.7	2.7	0.78	0.58
Lea	LE11 Arbina	14.75	13.9	101.3	116.3	14.8	0.83	0.83
Oka	OK01 Muxika	28.75	2.1	48.0	46.8	-2.4	0.81	0.90
Oka	SA06 Olalde	7.25	1.3	10.9	6.5	-40.3	0.40	0.20
Ibaizabal	NB05 Abusu	1021.00	8.3	4677.6	5052.4	8.0	0.79	0.78
Ibaizabal	NB01 Saratxo	93.50	11.8	401.2	529.8	32.1	0.63	0.76
Ibaizabal	CHN164 Lemoa	143.75	7.4	905.8	689.1	-23.9	0.54	0.72
Ibaizabal	CHN163 Lemoa	256.00	30.3	7967.1	6209.0	-22.1	0.49	0.69
Ibaizabal	NB04 Zaratamo	522.25	13.4	3268.6	3221.9	-1.4	0.80	0.91
Ibaizabal	UNDU Undurraga	31.25	26.9	736.1	723.9	-1.7	0.49	0.64
Ibaizabal	IB32 Urkizu	136.50	11.0	815.1	1088.0	33.5	0.73	0.67
Ibaizabal	NB11 Orozco	118.00	8.4	484.2	476.8	-1.5	0.71	0.87
Ibaizabal	NB02 Gardea	193.50	5.3	363.1	377.6	4.0	0.71	0.92

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Table 4. Continued.

Basin	Gauge station	Area km ²	N° years	Obs Vol Hm ³	Sim Vol Hm ³	%errVol	E daily	E monthly
Ibaizabal	IB21 Oromiño	20.50	11.0	156.9	172.6	10.0	0.13	−0.31
Ibaizabal	CHN175 Güeñes	258.25	30.3	4789.3	2887.7	−39.7	0.34	0.53
Ibaizabal	KD12 Herrerías	258.25	3.7	241.6	288.7	19.5	0.80	0.87
Ibaizabal	E. Maroño	21.50	13.0	168.0	125.8	−25.1	0.49	0.63
Ibaizabal	IB01 Elorrio	29.75	0.3	8.6	8.3	−3.9	0.22	0.27
Ibaizabal	IB03 Amorebieta	225.00	2.5	454.8	395.4	−13.1	0.80	0.90
Ibaizabal	E. Artziniega	12.00	12.4	89.4	68.4	−23.4	−0.40	−0.18
Karrantza	KR01 Karrantza	114.75	13.8	587.7	635.9	8.2	0.29	0.41
Omeçillo	CHE188 Berguenda	345.75	18.8	1553.9	1428.2	−8.1	0.54	0.72
Omeçillo	OSM1 Osmá-1	79.00	14.8	455.7	482.0	5.7	0.39	0.76
Omeçillo	OSM2 Osmá2	71.50	14.8	273.5	471.5	72.4	0.11	0.36
Baia	APRI Aprikano	196.25	11.6	1323.9	1330.0	0.5	0.52	0.72
Baia	POBE Pobes	234.50	11.6	1409.7	1500.7	6.5	0.60	0.84
Baia	CHE165 Miranda	306.75	20.0	3512.8	3132.1	−10.8	0.49	0.60
Zadorra	CHE074 Arce	1358.50	33.1	19722.0	21512.0	9.1	0.65	0.82
Zadorra	CHE108 Urrunaga	142.00	44.8	73471.7	57633.3	−21.6	0.40	0.79
Zadorra	CHE107 E. Ullibarri	272.50	44.8	7174.7	7016.2	−2.2	0.59	0.87
Zadorra	H152 Audicana	89.50	27.0	1168.0	1117.4	−4.3	0.57	0.75
Zadorra	H154 Ozaeta	86.00	28.1	1518.8	1688.4	11.2	0.66	0.75
Zadorra	CHE221 Larrinoa	19.25	19.0	359.9	283.2	−21.3	0.69	0.73
Zadorra	CHE075 Berantevilla	308.00	48.8	5079.9	5312.3	4.6	0.56	0.69
Zadorra	H153 Otxandio	34.75	17.3	716.6	468.0	−34.7	0.44	0.67
Zadorra	CHE204 Matauko	98.00	8.0	329.5	324.4	−1.6	0.36	0.39
Ega	G313 Ancin	472.50	14.3	1777.8	1820.5	2.4	0.78	0.89
Ega	G314 Murieta	544.75	14.3	2268.6	2128.9	−6.2	0.73	0.85
Arakil	G433 Etxarren	401.50	11.6	3199.4	3110.8	−2.8	0.76	0.88

Table 5. Summary of mean results after 40 or 50 years of simulation (ungauged points do not have station code and can be identified by capital letters D. and E., PPT: Precipitation in mm/year, PET: Potential evapotranspiration in mm/year, RET: Real evapotranspiration in mm/year, Q sim: Observed discharge in mm/year, V sim: Simulated volume, UL: underground losses in mm/year, DR: Surface runoff, IF: Interflow, BF: Base flow).

Gauge station or ungauged point	Area km ²	PPT	PET	RET Sim	Q Hm ³	V Sim	UL %	DR %	IF %	BF
D. Aldabe	15.50	1843	850	699	1143	17.7	0	26.9	39.0	34.1
D. Endara	19.25	2131	846	801	1327	25.6	0	7.0	52.2	40.9
D. Jaizubia	33.00	1728	857	669	1057	34.9	0	33.6	35.9	30.5
E. San Antón	10.75	2187	847	829	1355	14.6	0	8.5	51.6	39.9
F1Z1 Endara	5.75	2215	849	831	1382	7.9	0	9.2	50.8	40.0
E1Z1 Oiartzun	57.25	1975	856	791	1182	67.7	0	10.8	49.4	39.7
CHN107 Oiartzun	35.50	2070	859	807	1261	44.8	0	9.0	51.3	39.7
D. Oiartzun	81.00	1905	851	750	1153	93.4	0	16.9	45.2	37.9
CHN105 Ereñozu	213.00	2341	829	792	1546	329.2	0	3.6	59.6	36.8
D2Z1 Ereñozu	212.50	2343	829	792	1547	328.7	0	3.6	59.6	36.8
D1W1 Añarbe	46.75	2558	822	782	1772	82.8	0	4.8	63.0	32.1
E. Añarbe	60.75	2466	826	783	1680	102.1	0	4.6	61.0	34.4
D. Urumea	268.25	2216	816	750	1464	392.7	0	7.7	56.1	36.2
D. Igarra	19.25	1516	669	521	994	19.1	0	27.4	38.5	34.1
C9Z1 Lasarte	805.50	1643	822	754	886	713.9	0	26.7	38.6	34.7
C2Z1 Agauntza	73.00	1503	784	734	767	56.0	0	26.4	36.4	37.3
C7Z1 Belauntza	32.75	1931	839	779	1149	37.6	0	33.5	31.7	34.9
C8Z1 Andoain L	114.75	2029	843	810	1216	139.5	0	19.2	46.5	34.3
CHN080 Andoain O	785.25	1641	822	755	883	693.5	0	26.4	38.6	35.0
C5Z1 Alegia	344.00	1433	823	754	676	232.7	0	26.7	39.8	33.5
C3T1 Amundarain	16.25	2167	632	602	1566	25.4	0	24.5	59.2	16.3
E. Arrian	9.25	1364	859	790	574	5.3	0	29.7	41.6	28.7
E. Lareo	0.25	1586	748	706	876	0.2	0	27.1	45.2	27.8
E. Ibiur	11.50	1536	846	775	761	8.8	0	23.0	19.5	57.5
D. Iñurritza	20.00	1467	828	736	732	14.6	0	30.1	42.2	27.7
C1Z2 Estanda	57.00	1368	863	787	580	33.1	0	22.2	49.4	28.4
D. Oria	887.25	1637	820	751	886	786.2	0	27.0	39.0	34.0
CHN109 Etxabe	310.50	1589	794	720	867	269.3	0	23.5	41.2	35.3
B1Z2 Ibai Eder	64.50	1595	792	743	852	54.9	0	12.9	50.4	36.7
E. Ibaieder	29.00	1612	790	741	871	25.2	0	14.0	48.4	37.6
B2S1 Granadaerre	2.25	1746	778	715	1030	2.3	0	33.2	38.3	28.5
B1Z1 Aitzu	59.75	1645	792	705	937	56.0	0	26.4	44.4	29.2
E. Barrendiola	4.00	1662	799	750	909	3.6	0	22.0	46.7	31.3
B2Z1 Aizarnazabal	277.50	1596	795	720	874	242.6	0	23.1	42.0	34.9
D. Urola	346.00	1567	792	714	852	294.7	0	24.0	40.7	35.3

Table 5. Continued.

Gauge station or ungauged point	Area km ²	PPT	PET	RET Sim	Q Hm ³	V Sim	UL %	DR %	IF %	BF
A3Z1 Altzola	469.00	1597	851	758	837	392.7	0	27.7	47.8	24.5
E. Aixola	7.75	1734	832	774	958	7.4	0	34.3	40.9	24.8
A2Z1 Aixola	4.50	1743	833	767	975	4.4	0	37.2	37.5	25.3
E. Urkulu	13.00	1582	822	708	873	11.4	0	33.1	18.1	48.8
A1Z3 Urkulu	8.00	1624	805	678	945	7.6	0	30.4	21.8	47.8
A1Z2 Zubillaga	106.25	1610	790	714	894	95.0	0	26.8	44.5	28.7
A1Z1 San Prudentzio	127.25	1457	874	770	686	87.3	0	23.6	50.8	25.6
D. Deba	531.75	1614	851	761	851	452.6	0	29.1	46.8	24.2
D. Saturrarán	17.25	1597	847	782	815	14.1	0	30.5	40.8	28.6
AR01 Iruzubietia	25.50	1594	800	753	838	21.4	0	31.1	41.4	27.5
CHN141 Berriatua	94.00	1529	804	747	778	73.2	0	37.9	36.4	25.7
D. Artibai	106.75	1514	804	747	764	81.6	0	37.3	36.1	26.6
LE01 Aulestia	37.75	1519	726	664	857	32.3	0	30.1	35.2	34.7
LE11 Arbina	14.75	1358	726	660	700	10.3	0	27.6	33.1	39.3
D. Lea	82.00	1422	726	652	771	63.2	0	33.4	28.3	38.3
D. Ea	18.50	1305	723	645	662	12.3	0	22.5	35.4	42.1
OK01 Muxika	28.75	1497	763	671	824	23.7	0	32.1	37.2	30.7
SA06 Olalde	7.25	1357	756	687	669	4.9	0	34.6	16.9	48.5
D. Oka	184.00	1409	760	665	742	136.6	0	34.9	34.1	31.0
D. Artigas	17.25	1320	761	686	634	10.9	0	22.9	47.4	29.7
D. Laga	12.50	1329	757	672	657	8.2	0	33.1	25.6	41.3
D. Estepona	24.25	1267	885	741	528	12.8	1	17.2	40.1	42.6
D. Arcega	5.00	1262	885	716	547	2.7	2	23.1	34.4	42.5
D. Andraka	7.50	1279	886	719	562	4.2	1	43.4	29.6	27.0
D. Butroe	175.00	1324	885	701	625	109.3	1	35.3	31.5	33.2
NB05 Abusu	1021.00	1436	924	768	667	680.9	0	33.2	42.5	24.3
NB01 Saratxo	93.50	1298	914	698	598	55.9	0	37.2	31.5	31.3
CHN164 Lemoa	143.75	1619	966	868	750	107.8	0	28.6	44.2	27.2
CHN163 Lemona	256.00	1593	900	776	816	208.9	0	39.5	38.1	22.4
NB04 Zaratamo	522.25	1315	924	748	566	295.5	0	27.8	45.3	26.9
UNDU Undurraga	31.25	1708	957	857	849	26.5	0	26.4	42.9	30.7
IB32 Urkizu	136.50	1626	965	870	754	102.9	0	28.3	44.3	27.4
NB11 Orozco	118.00	1291	898	736	554	65.4	0	24.8	43.9	31.3
NB02 Gardea	193.50	1233	927	704	528	102.2	0	34.2	37.1	28.7
IB21 Oromiño	20.50	1673	894	826	846	17.3	0	25.6	47.9	26.6
CHN175 Güeñes	258.25	1085	923	616	469	121.0	0	26.0	52.0	22.0
E. Maroño	21.50	1239	935	686	552	11.9	0	34.7	41.9	23.4
IB01 Elorrio	29.75	1634	882	782	851	25.3	0	43.4	38.0	18.6
IB03 Amorebieta	225.00	1607	895	769	836	188.1	0	40.7	37.0	22.3
D. Ibaizabal	1843.75	1357	908	691	665	1225.6	0	34.8	43.6	21.6
KD01 Balmaseda	208.75	1321	897	526	793	165.6	0	20.2	42.5	37.3
CHN177 Orduñe	46.25	1504	888	673	829	38.3	0	15.9	51.6	32.5
E. Artziniega	12.00	1049	922	436	612	7.3	0	37.0	45.0	18.0
E. Gorostiza	24.75	1588	848	777	809	20.0	0	19.0	60.8	20.2

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Table 5. Continued.

Gauge station or ungauged point	Area km ²	PPT	PET	RET Sim	Q Hm ³	V Sim	UL %	DR %	IF %	BF
D. Kadagua	601.75	1236	903	608	627	377.1	0	29.2	50.4	20.4
D. Barbadun	123.75	1235	775	582	654	80.9	1.1	39.5	35.1	25.3
CHN186 Guerizo	118.75	1273	799	629	640	76.0	0	36.2	41.3	22.5
D. Agüera	144.75	1266	801	607	661	95.7	0	39.6	39.5	20.9
D. Agüera CAPV	60.75	1289	790	624	667	40.5	0	40.4	37.4	22.2
KR01 Karrantza	114.75	1325.0	787.0	687.0	638	73.2	0.0	36.2	41.1	22.7
D. Calera	38.50	1328.0	790.0	654.0	672	25.9	0.0	42.3	35.8	21.9
CHE188 Berguenda	345.75	776	956	529	246	84.9	0	28.4	24.4	47.2
OSM1 Osma-1	79.00	845	949	391	451	35.7	0	38.0	21.2	40.8
D. Omecillo	354.75	773	956	527	245	86.7	0	28.4	24.7	46.9
OSM2 Osma2	71.50	851	947	382	466	33.4	0	39.0	20.6	40.4
APRI Aprikano	196.25	1212	739	592	618	121.3	0	27.4	37.3	35.3
POBE Pobes	234.50	1169	740	581	586	137.5	0	29.3	34.9	35.9
CHE165 Miranda	306.75	1066	741	547	517	158.7	0	28.1	35.5	36.4
CHE074 Arce	1358.50	1012	934	518	491	666.5	0	11.9	39.0	49.1
CHE108 Urrunaga	142.00	1500	938	726	770	109.4	0	9.6	52.1	38.3
CHE107 E. Ullibarri	272.50	1132	907	562	565	154.0	0	12.3	40.0	47.7
H152 Audicana	89.50	997	914	512	481	43.0	0	5.5	35.9	58.6
H154 Ozaeta	86.00	1426	864	698	723	62.2	0	4.1	45.4	50.5
CHE221 Larrinoa	19.25	1547	946	759	783	15.1	0	6.0	36.3	57.7
CHE075 Berantevilla	308.00	789	948	406	379	116.8	0	3.3	36.1	60.6
H153 Otxandio	34.75	1672	919	788	879	30.6	0	4.4	56.6	39.0
CHE204 Matauko	98.00	908	952	511	393	38.6	0	9.8	35.3	54.8
E. Gorbea II	10.00	1723	943	772	947	9.5	0	6.5	33.2	60.3
E. Albina	9.75	1324	932	718	602	5.9	0	10.2	49.7	40.1
OCIO Ocio	86.00	754	1026	596	110	9.5	48	16.3	1.4	82.3
SA01 Peñacerrada	48.25	804	1037	648	106	5.1	51	12.2	0.6	87.2
D. Inglares	97.50	736	1023	581	110	10.7	45	21.3	1.3	77.4
G313 Ancin	472.50	871	655	487	369	174.6	14	2.4	28.0	69.6
G314 Murieta	544.75	876	656	472	389	211.8	15	7.8	25.8	66.4
CHE006 Marañon	89.00	874	655	491	370	32.9	13	2.9	30.1	67.0
D. Ega CAPV	403.25	832	634	466	352	141.9	13	2.1	28.3	69.6
SA05 Zarpia	10.75	1684	0	731	778	0.0	0	1.0	6.0	94.0
D. Larrondoa	27.00	1723	970	711	1008	27.2	0	8.4	1.2	90.4
G433 Etxarren	401.50	1314	765	559	751	301.5	0	24.7	44.8	30.5
D. Arakil CAPV	85.50	1141	756	530	606	51.8	0	13.1	37.6	49.3
D. Barriobusto	63.75	475	1019	185	289	18.4	0	87.2	4.1	8.7
D. El-Lago	15.25	663	976	457	203	3.1	0	0.7	47.1	52.2
D. Herrera	27.25	554	1005	298	254	6.9	0	64.7	13.3	22.0
D. Riomayor	49.75	525	1004	372	150	7.5	0	11.0	30.6	58.4
D. San Ginés	75.75	523	1008	350	171	12.9	0	20.1	25.0	54.9
D. Purón	27.00	765	900	559	204	5.5	0	32.5	21.4	46.1
D. Valahonda	8.25	575	964	413	160	1.3	0	16.0	48.6	35.4
D. Yécora	28.75	466	1031	280	184	5.3	0	60.2	12.0	27.8

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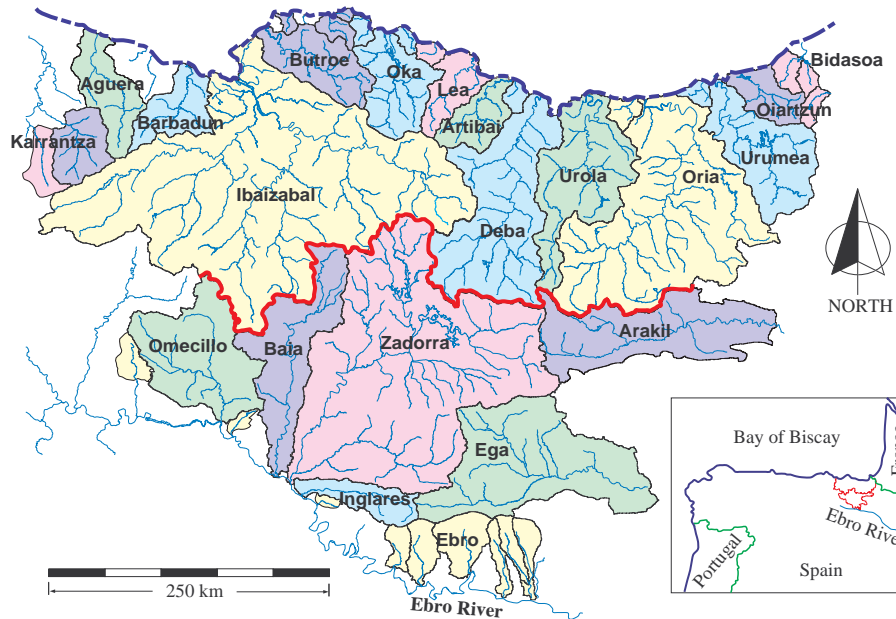


Fig. 1. Division of the study area in 21 systems (different colours) and 41 basins. Thick red line divides the study area into northern and southern basins.

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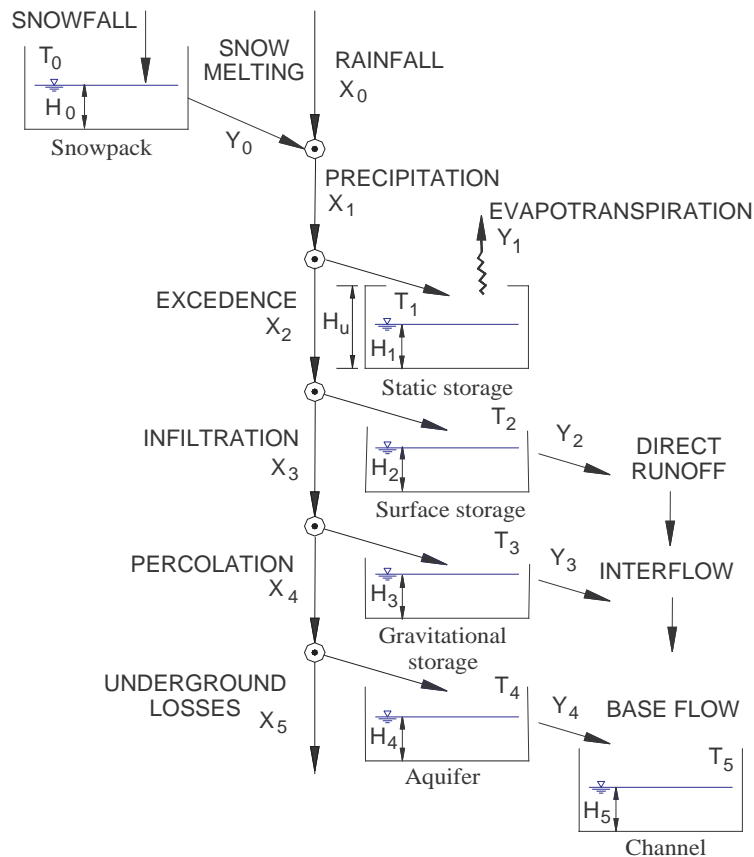


Fig. 2. Runoff production in TETIS model and conceptual scheme of vertical movement at cell scale (Francés et al., 2007).

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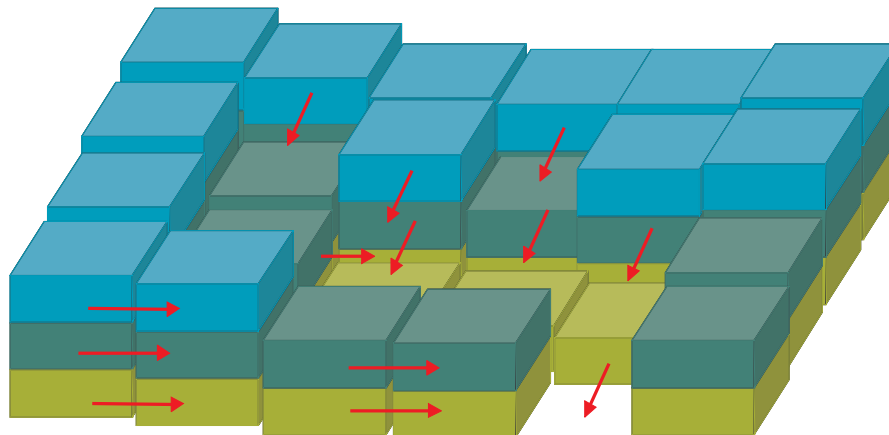


Fig. 3. Three-dimensional scheme of TETIS model indicating the horizontal movement among cells (Vélez, 2001).

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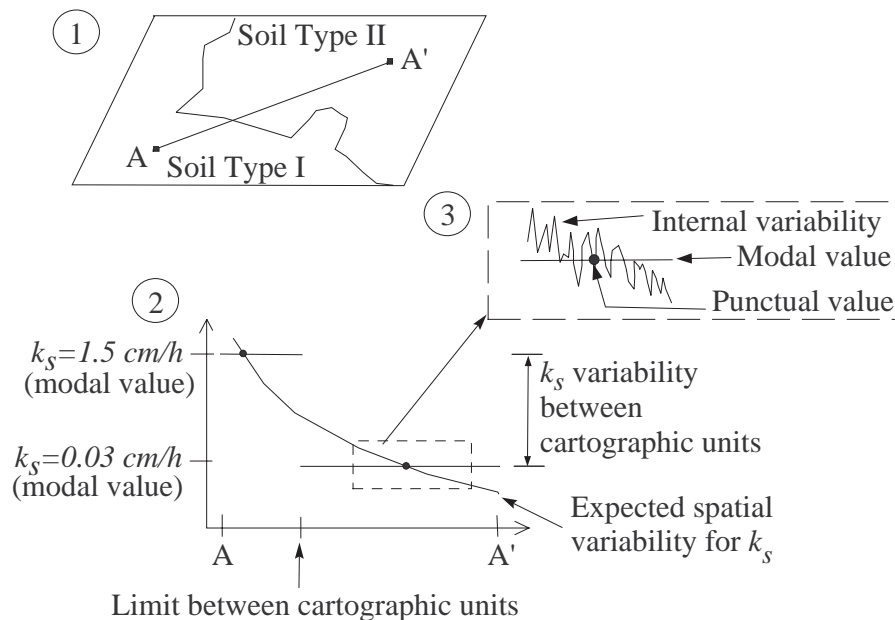


Fig. 4. Spatial variability between cartographic units (Puricelli, 2003).

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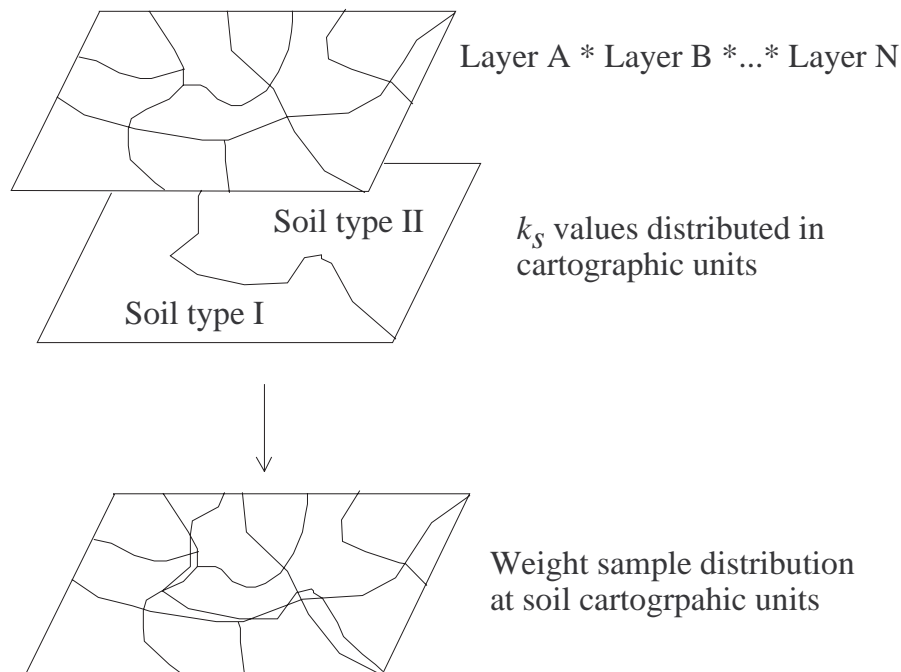


Fig. 5. Sample weights at cartographic units (Puricelli, 2003).

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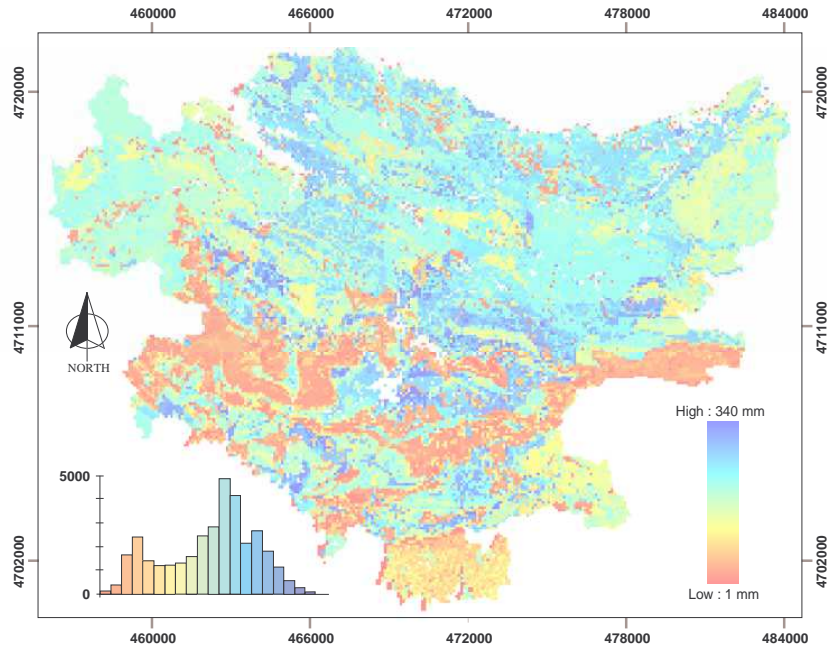


Fig. 6. Results of initial estimation of parameter map, H_u , in mm. The frequency histogram is in the lower left corner.

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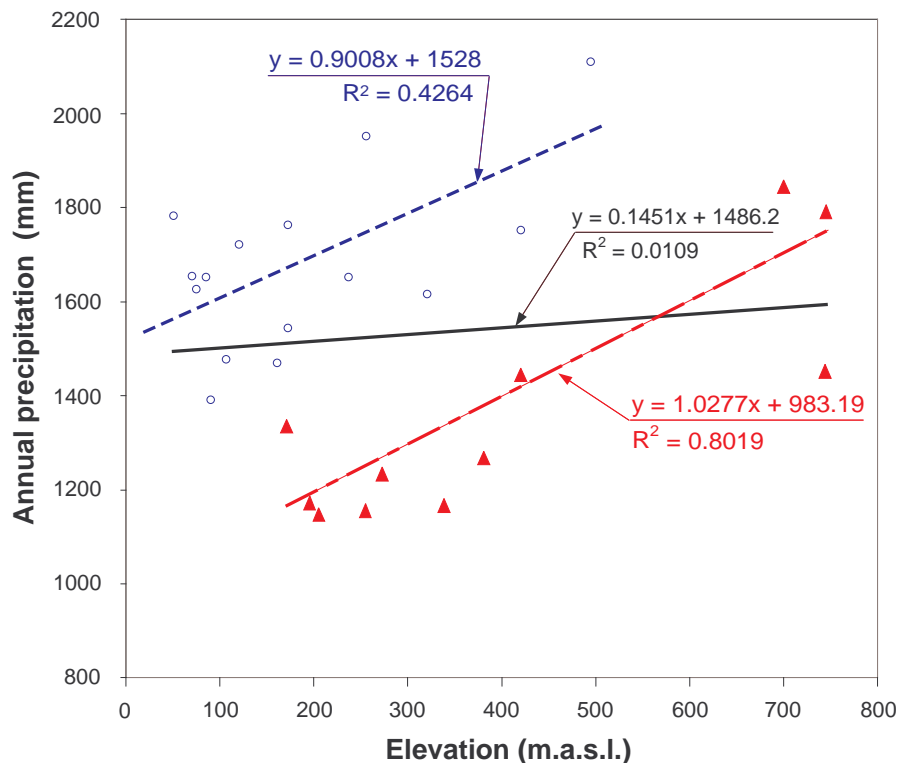


Fig. 7. Relationship between elevation and annual precipitation at Oria River basin (The circles belong to the lower zone; and the triangles belong to the upper zone, the continuous line represents the adjustment including all points, the dashed line represents the adjustment of the lower zone and the dashed-dot line represents the adjustment including the upper zone filled triangles).

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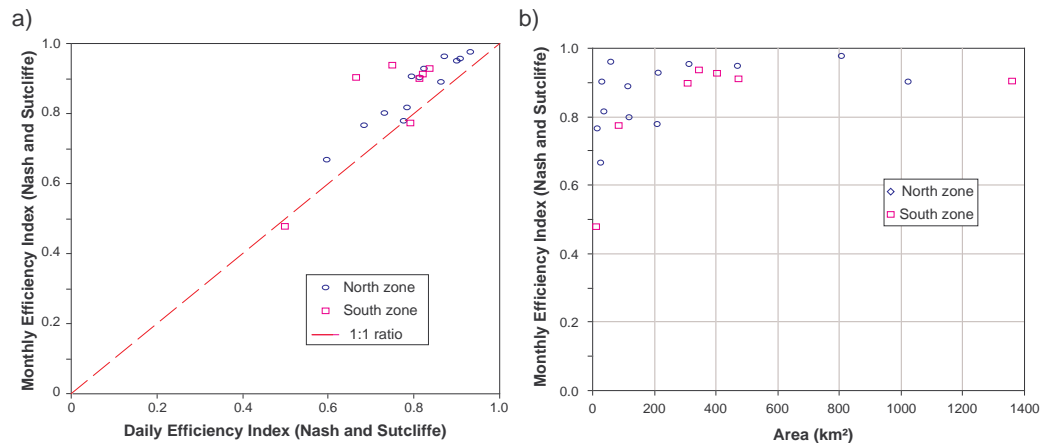


Fig. 8. Calibration results, monthly efficiency index versus: **(a)** Daily efficiency index, **(b)** Area. (North zone is identified by circles and South zone is represented by small squares).

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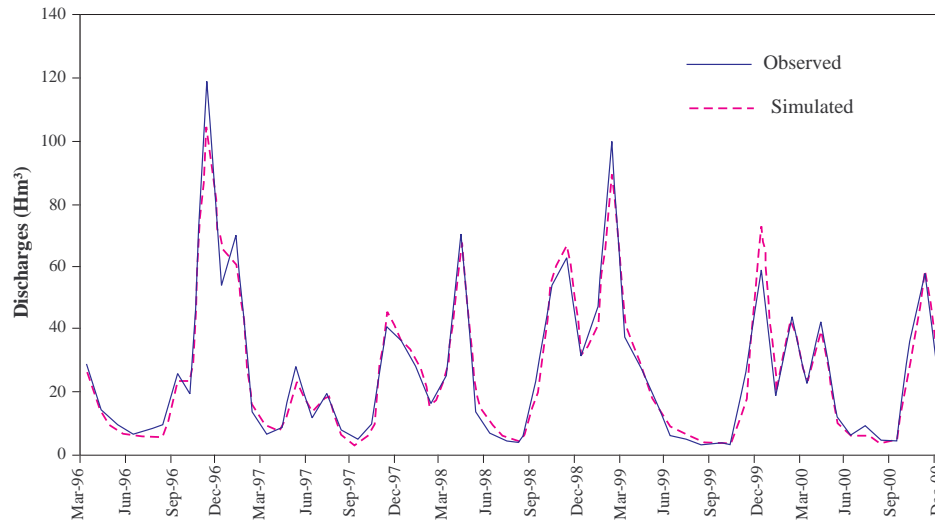


Fig. 9. Calibration results at “A3Z1 Altzola” gauge station on Deba River basin, which have been aggregated at monthly scale (Continuous line is the observed flow and dashed line is the simulated flow).

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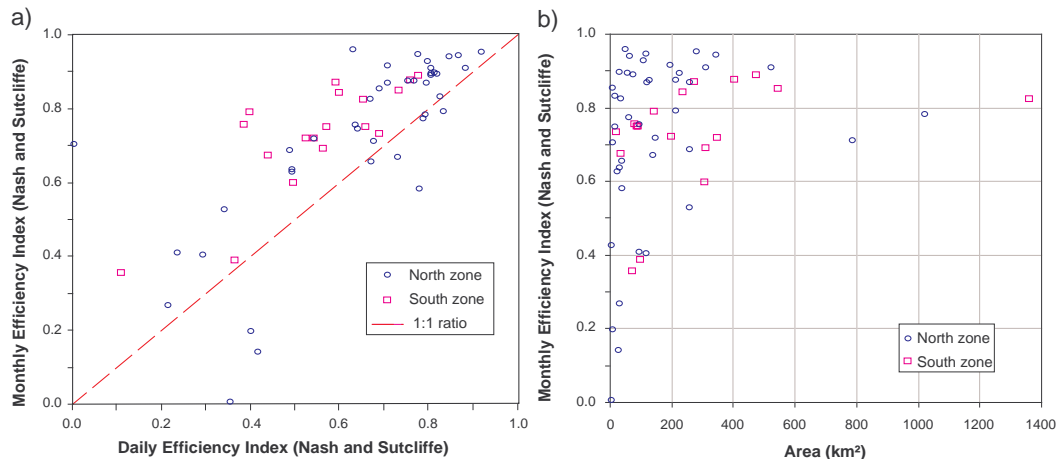


Fig. 10. Validation results, monthly efficiency index versus: **(a)** Daily efficiency index, **(b)** Area. (North zone is identified by points and South zone is represented by small squares points).

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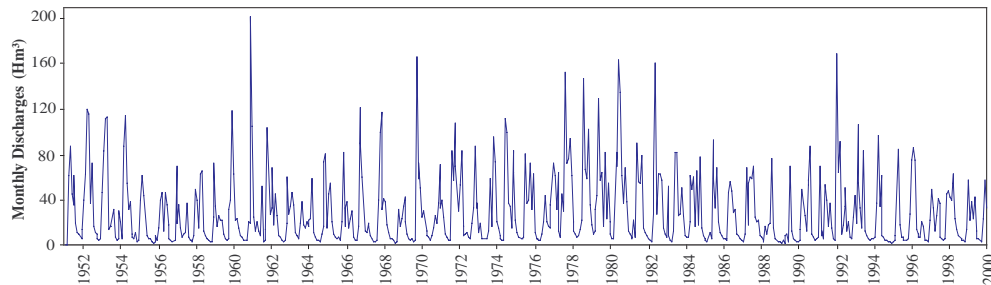


Fig. 11. Simulation results from 1951–2000 at downstream point at Deba River basin.

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